Millimeter/Submillimeter Observations of Young Disks

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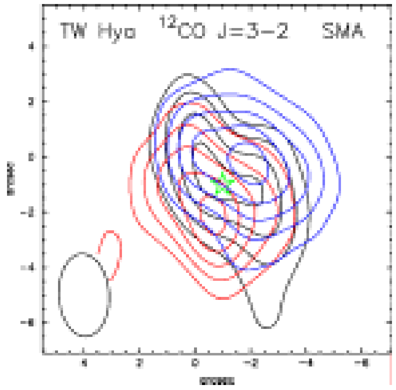
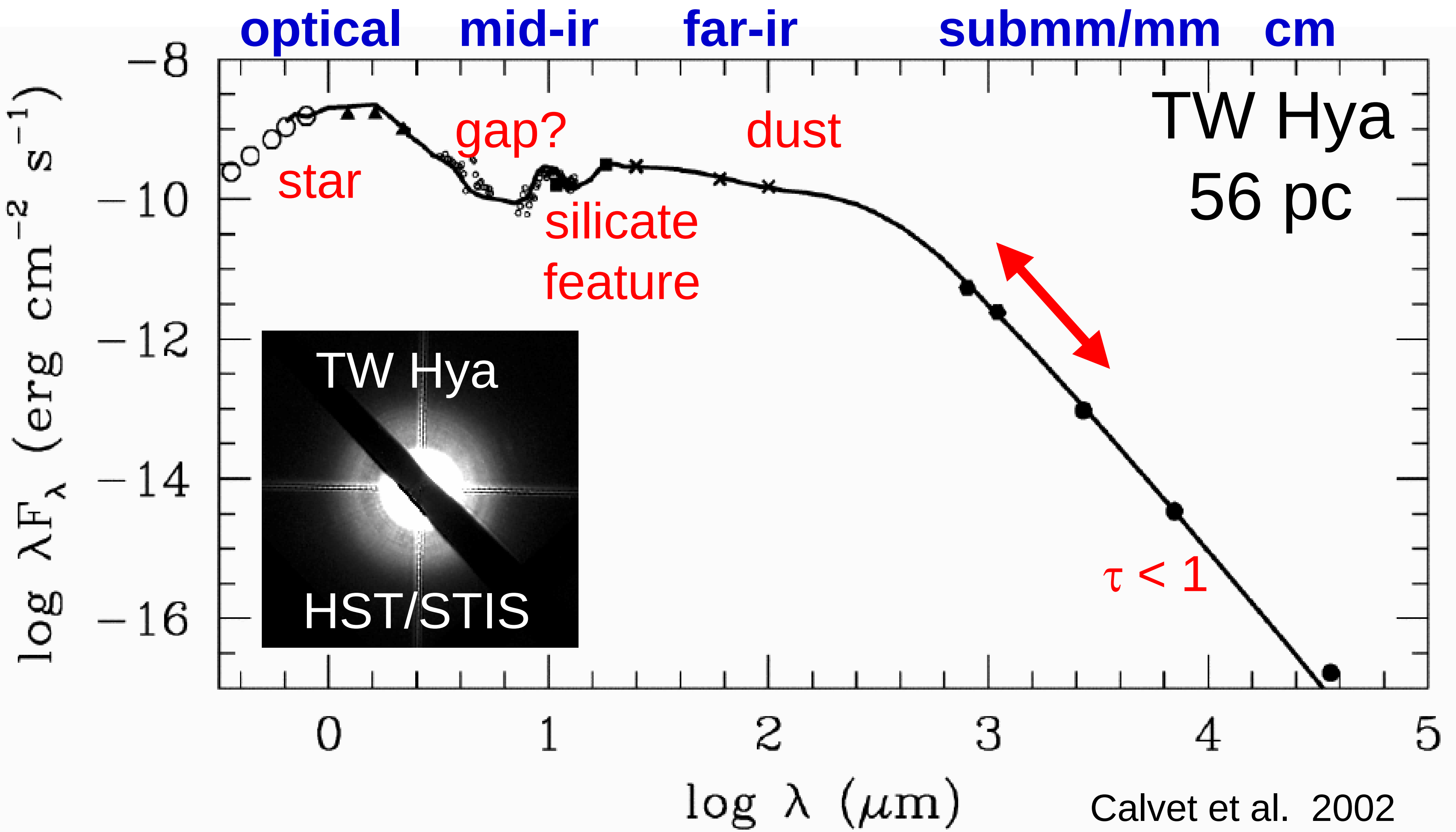
- Relevance of Millimeter Wavelengths
- Interferometry, Recent Results
  T-Tauri/HAeBe stars ~0.5-2.5 $M_\odot$
  – resolved structure, kinematics
  – evidence for grain growth



Why Millimeter/Submillimeter?

- bulk of disk material is "cold" H_2 ,
  T_k ~30 K at r ~100 AU for a T-Tauri star
- dust continuum emission with low τ:
  $dF_\nu = B_\nu(T)\ \kappa_\nu \Sigma\ dA$, i.e. millimeter flux prop. to mass weighted by temperature;
  $M_{disk} \sim 0.001 - 0.1\ M_\odot$ (Beckwith et al. 1990)
- trace molecular species, heterodyne spectroscopy $\delta\nu/\nu > 10^6$: kinematics, chemistry
- no contrast problem with stellar photosphere

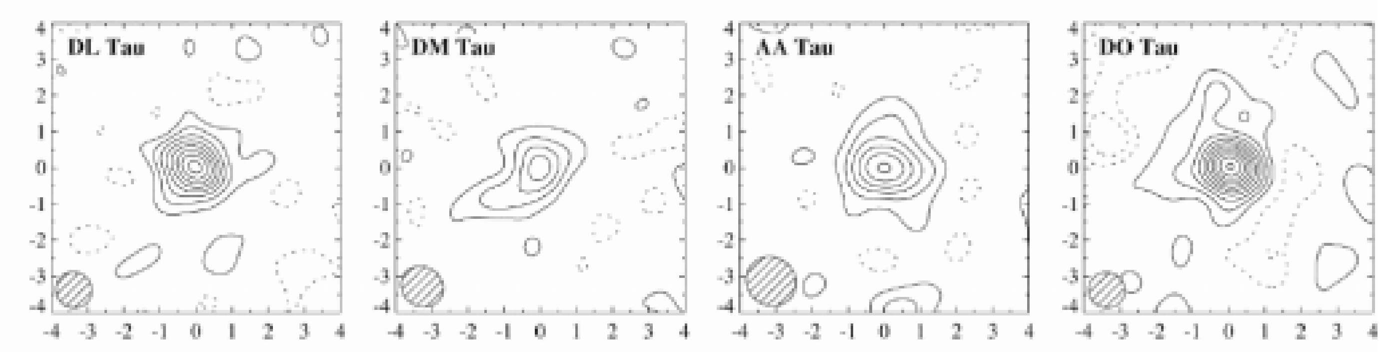
Spectral Energy Distribution



Calvet et al. 2002

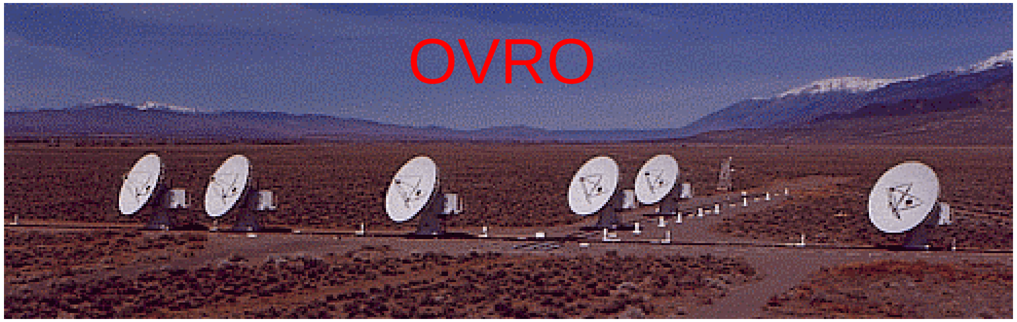
Millimeter Interferometry

- nearest star forming regions with large samples of pre-main-sequence star disks: 140 pc
  - R ~ 400 AU disk ~ 3 arcsec
  - R ~ 40 AU Kuiper Belt ~ 0.3 arcsec
  - dR ~ 1 AU gap by giant planet ~ 0.007 arcsec
- "routine" 3 to 1.3 mm dust imaging with ~mJy sensitivity, $\theta > 0.5$ arcsec (phase fluctuations)



NMA 2.1mm Taurus survey Kitamura et al. 2002

Millimeter Interferometry: Facilities

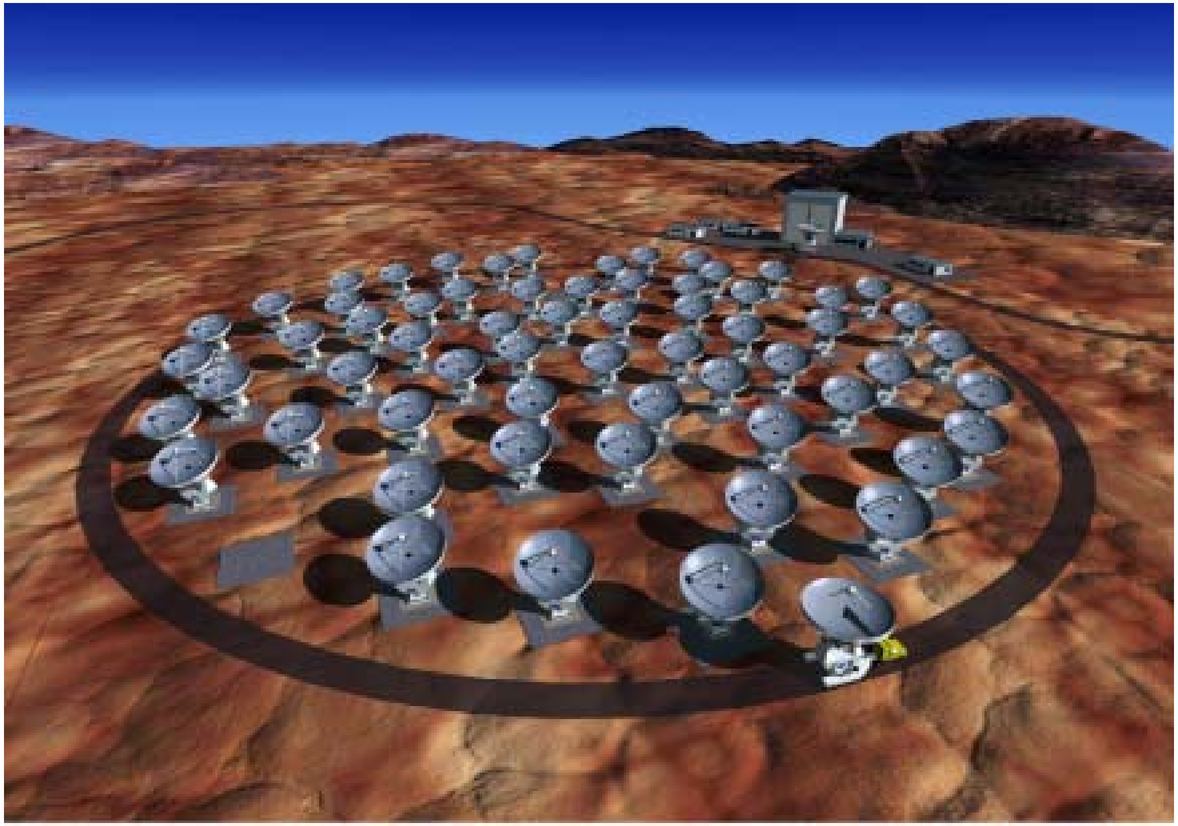


New Developments

- BIMA+OVRO = CARMA on higher site, 2005
- ATCA: 3 mm band deployed on 3 telescopes (5 in 2004), first access to far southern sky
- SMA: opens submillimeter 850, 450 μm atmospheric windows from Mauna Kea
- VLA: 7 mm + Pie Town link: 0.03 arcsec (sometimes); EVLA upgrades underway
- ALMA: best site, sensitivity, resolution; construction started (NA, Europe, Japan);

Atacama Large Millimeter Array

- large! 64 x 12m (+12 x 7m) telescopes; 18 km → < 0.01 arcsec at 870 μm



ALMA at Chajnantor

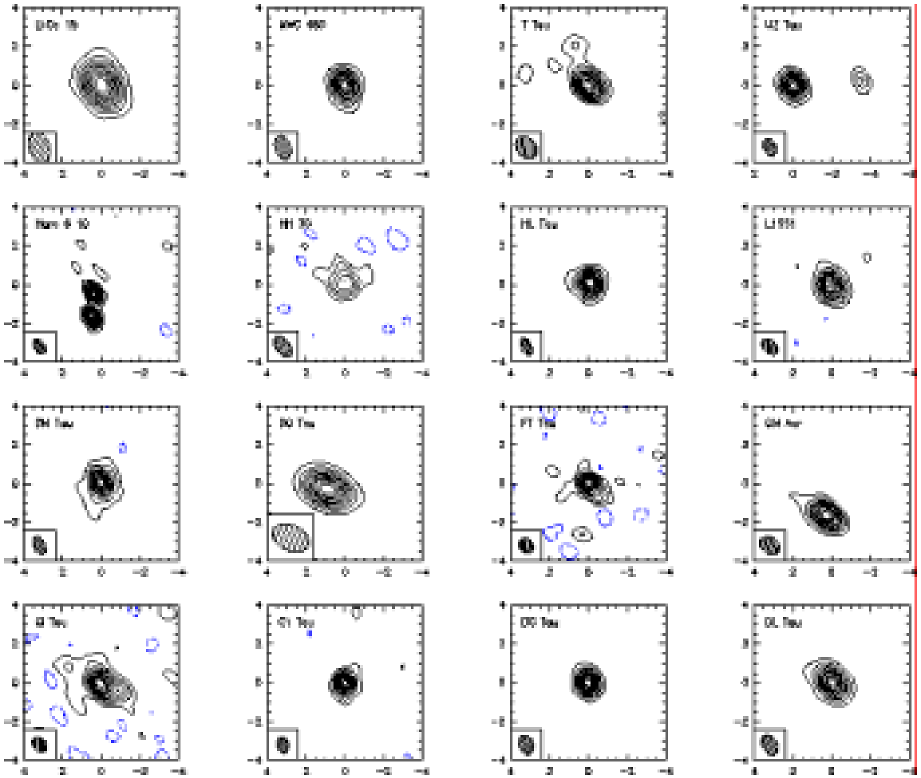
ESO PR Photo 06h/03 (25 February 2003)

early science: 2008
full operation: 2012

VertexRSI prototype antenna, Socorro, NM

Interferometer Imaging Surveys

- IRAM PdBI 2.7 mm (Dutrey et al. 1996):
  33 systems, ~10 dust resolved with high s/n;
  model $\Sigma \sim r^{-p}$, $T \sim r^{-q} \rightarrow p+q \sim 1.5$, $R > 150$ AU

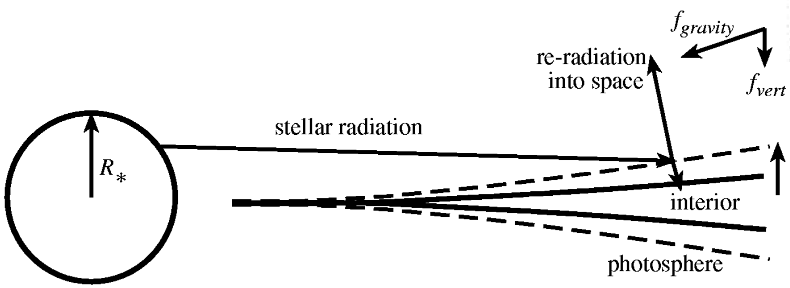


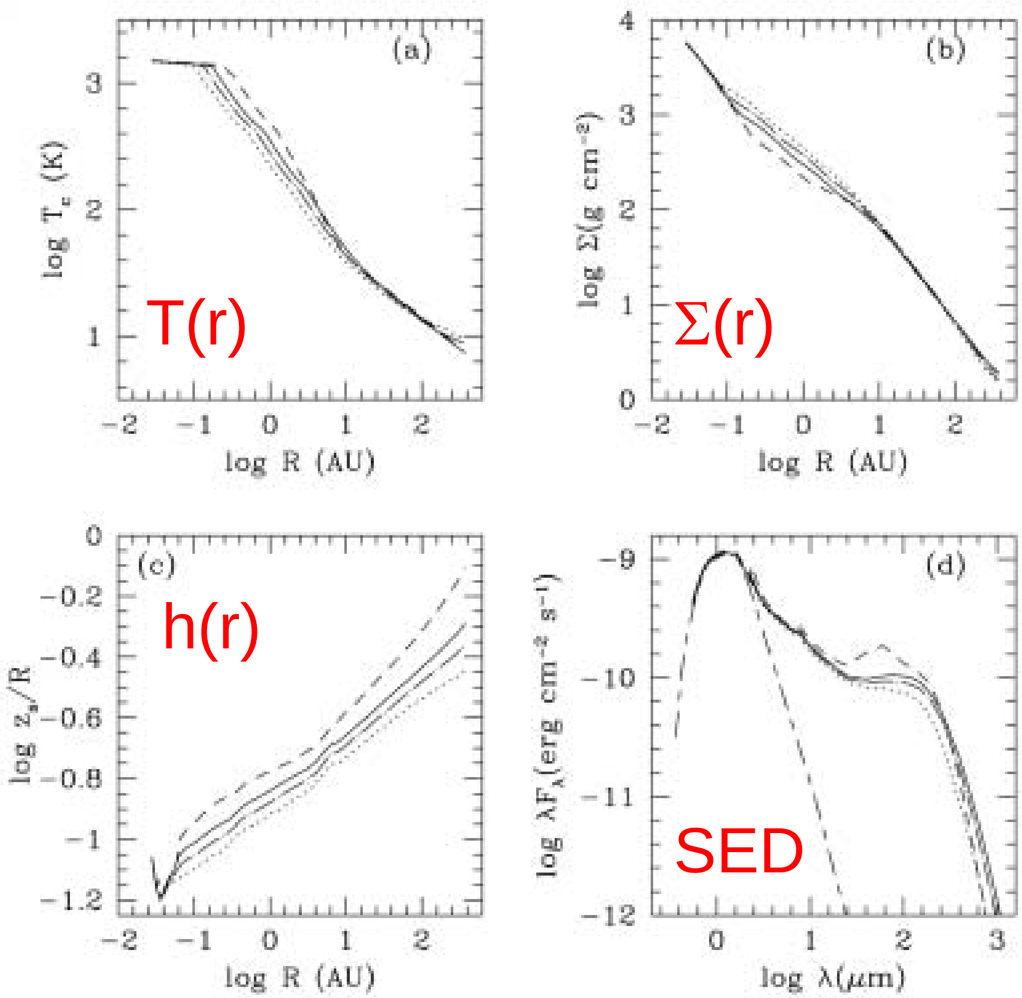
- IRAM PdBI 1.3 mm "mini-survey" confirms
  - elongations, p.a.'s
  - low dust opacities
  - "shallow" surface density profiles
  - "large" disk sizes

(Guilloteau, Dutrey)

Physical Models of Disk Structure

- replace power-law parameterizations with self-consistent radiative and hydrostatic equil.
- ~10^{-8} $M_{\odot}$/yr $\rightarrow$ irradiated, flared





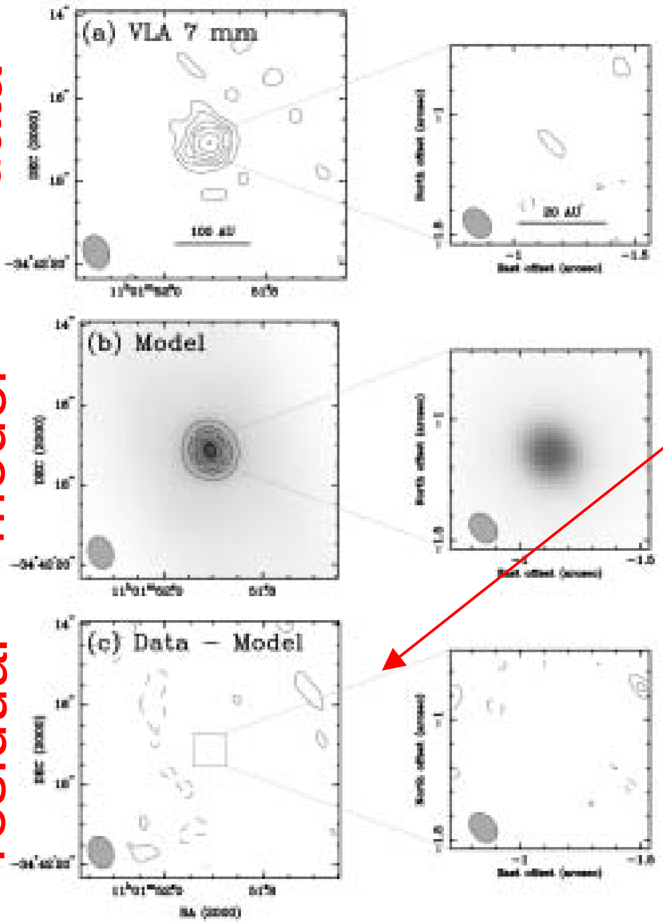
D'Alessio et al. 2001

Testing Disk Structure Models

data

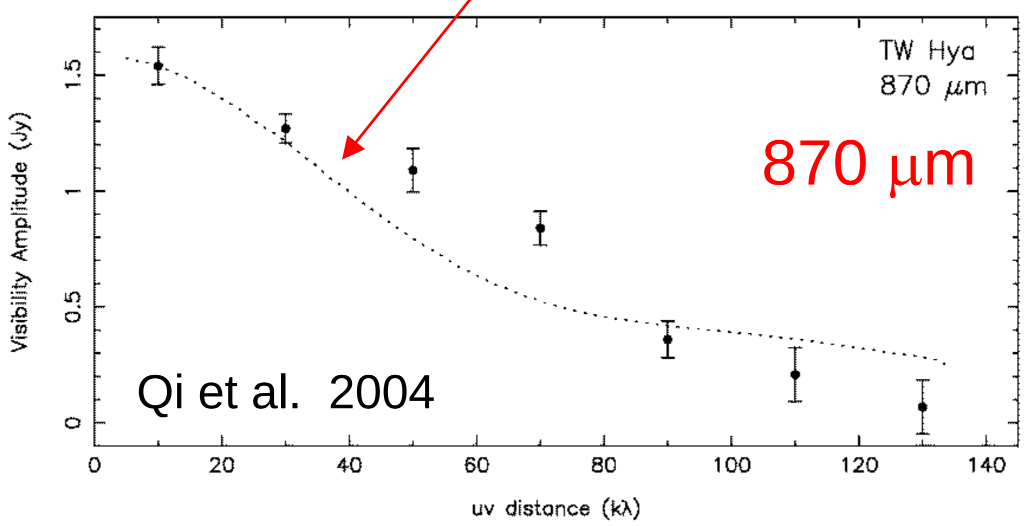
model

residual



Calvet et al. 2002

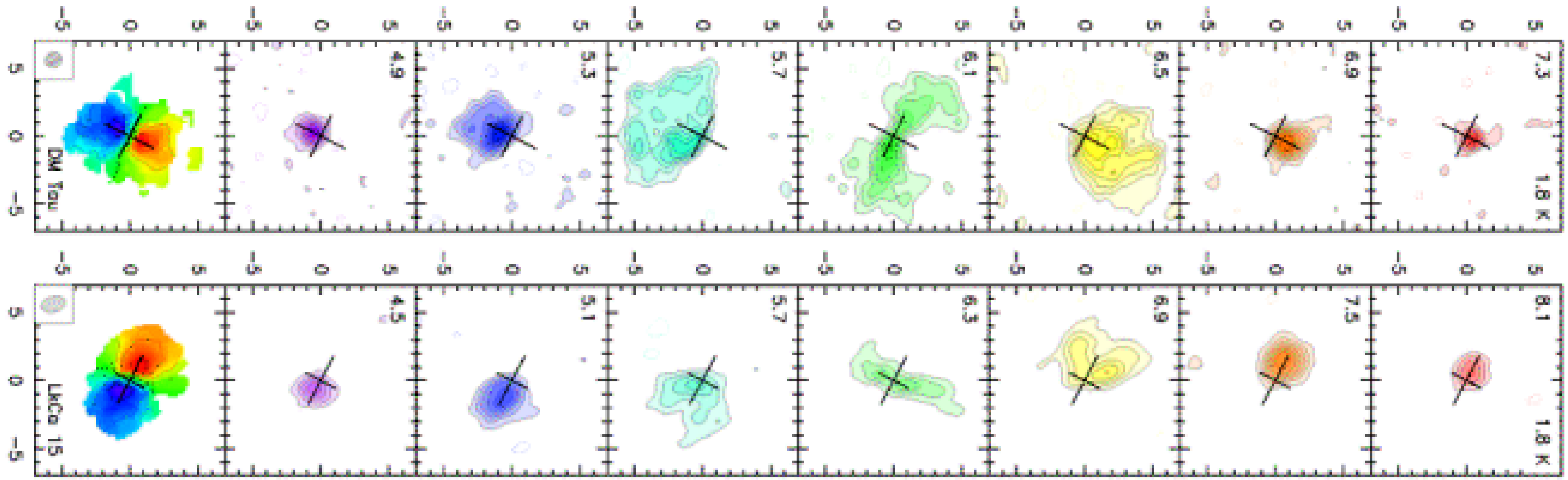
TW Hya: Calvet et al. (2002) irradiated accretion disk model matches full SED, VLA 7 mm, SMA 870 μm



Qi et al. 2004

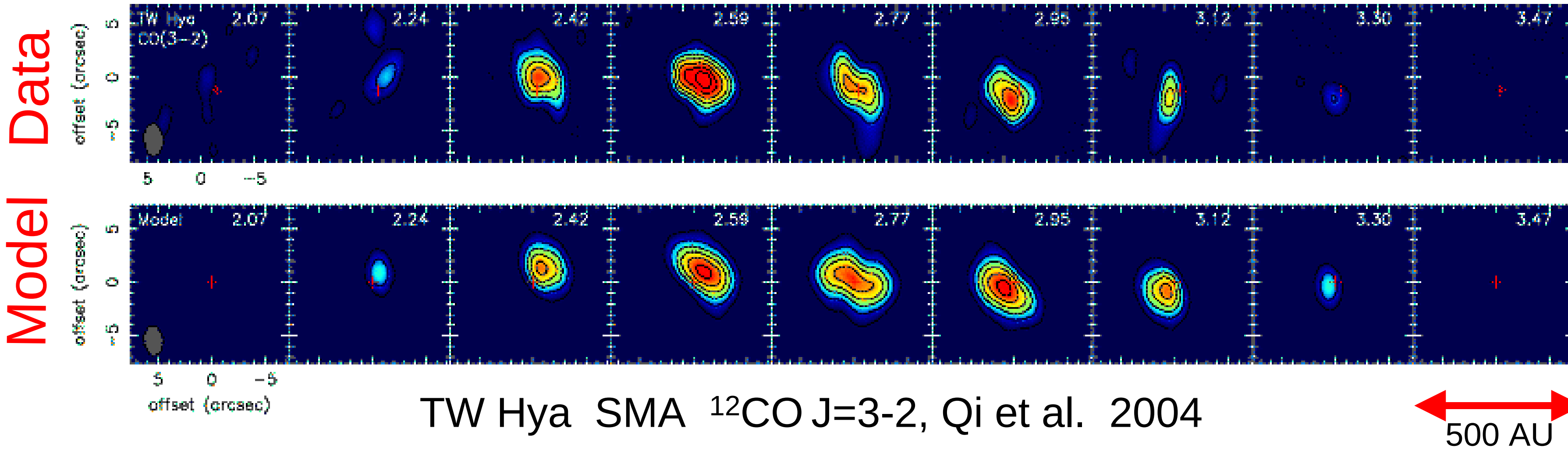
CO Line Observations

- CO most abundant tracer of "cold" H_2
- rot. lines collisionally excited, low J's thermalized
- optically thick: $T_k(r) \sim r^{-q} \rightarrow q = 0.5$ (flared)
- Keplerian rotation: $v(r/D) = (GM_*/r)^{0.5}\ \mathit{sin}\ i \rightarrow M_*$

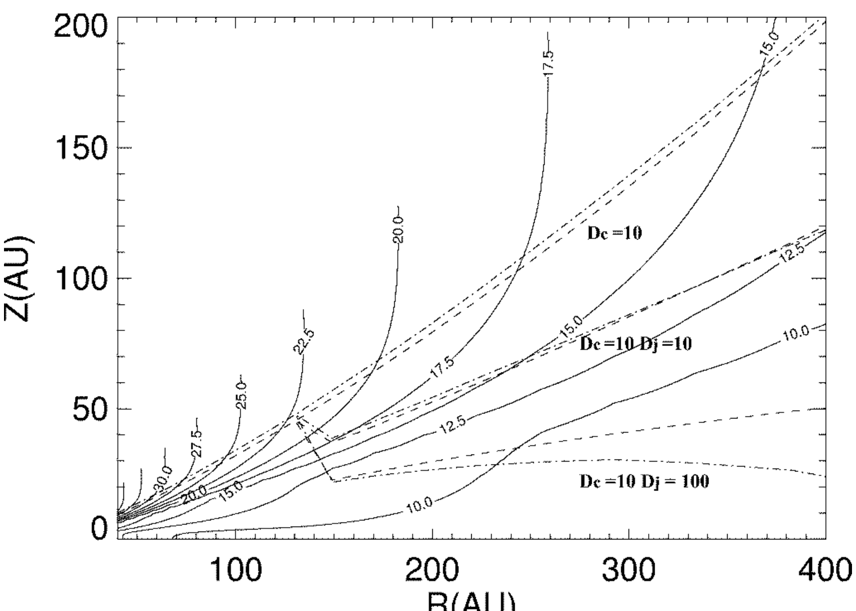


^{12}CO J=2-1 IRAM PdBI ~ 15 systems, e.g. Simon et al. 2000

CO Line Observations (cont)



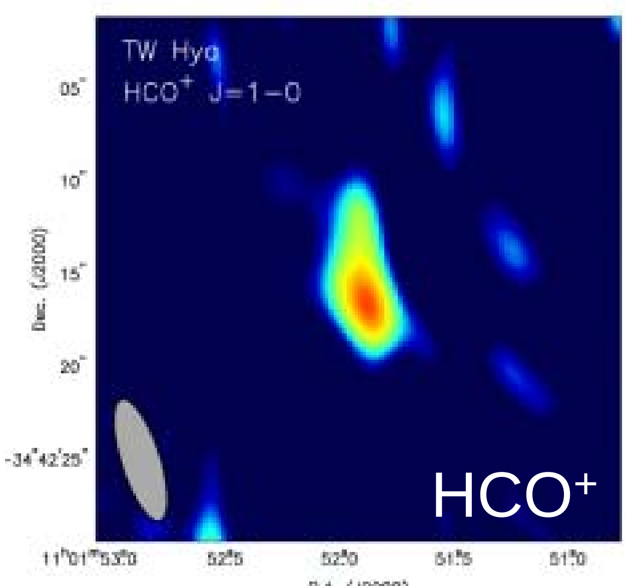
TW Hya SMA [12]CO J=3-2, Qi et al. 2004



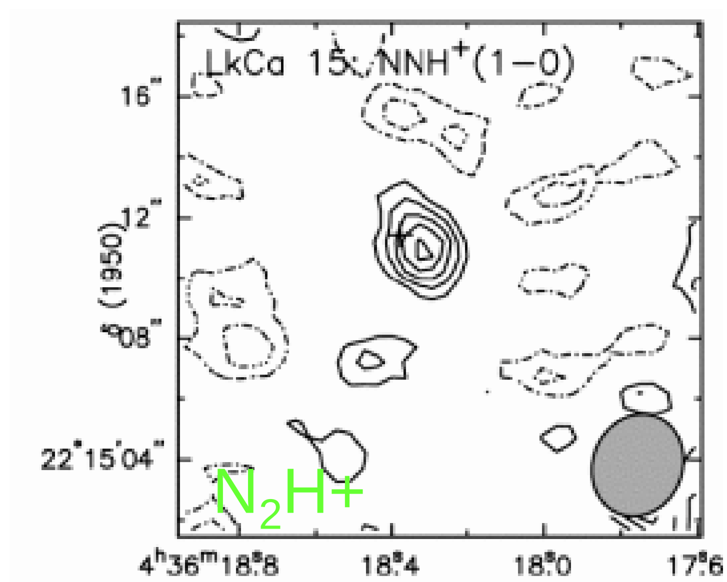
- inclination, orientation
- $\delta v_{turb} < 0.05$ km/s
- multiple lines: $T_k(r,z)$, untangle excitation abundance/depletion

Towards Nebular Chemistry

- single dish surveys of a handful of disks: abundant species, e.g. HCO^+, HCN, CS,... depletions 5 to >100x, photochemistry (CN, C_2H)
- imaging hard: low T_B for $\tau < 1$, Δv Doppler limited



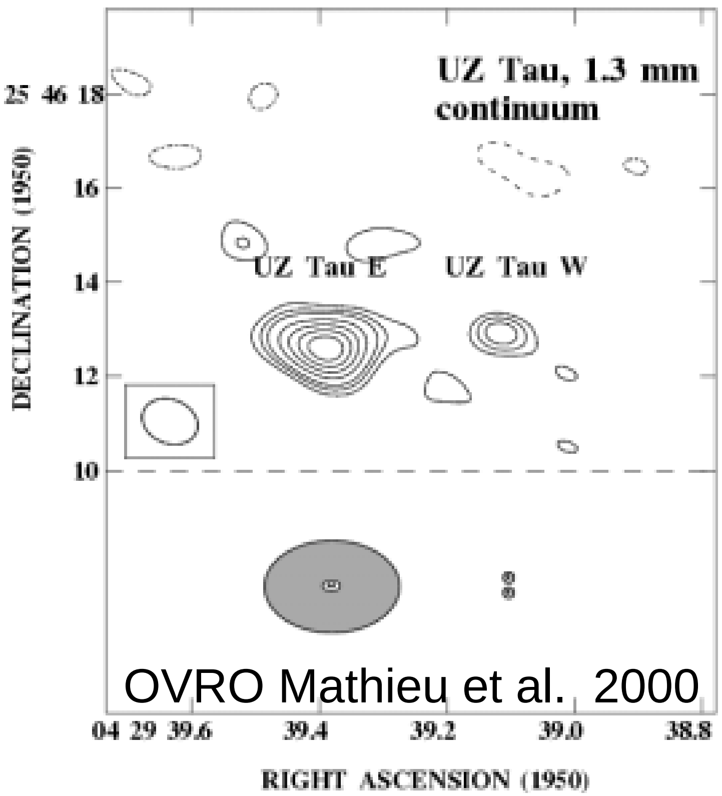
TW Hya ATCA Wilner et al. 2003



LkCa15 OVRO Qi et al. 2003

Effects of Stellar Multiplicity

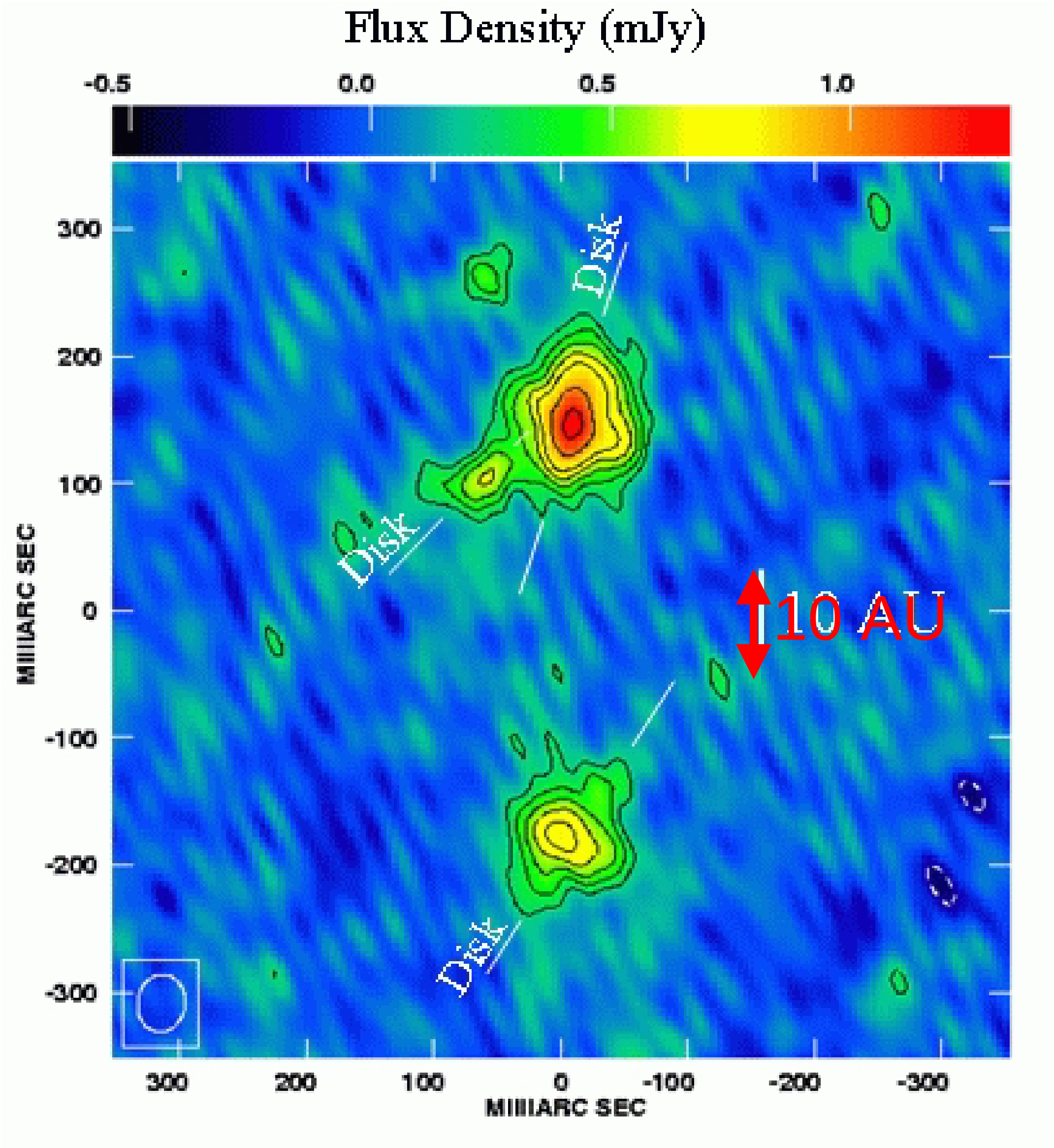
- millimeter fluxes generally lower in binaries, tidal truncation, i.e. disks within Roche lobes (Jensen et al. 1996); disks aligned, coplanar?



OVRO Mathieu et al. 2000

- UZ Tau Quadruple:
  - UZ Tau E
    0.03 AU a*sin* i binary: circumbinary emission (typical of single star)
  - UZ Tau W
    50 AU binary: weak circumstellar emission

Example: L1551 IRS5 Binary

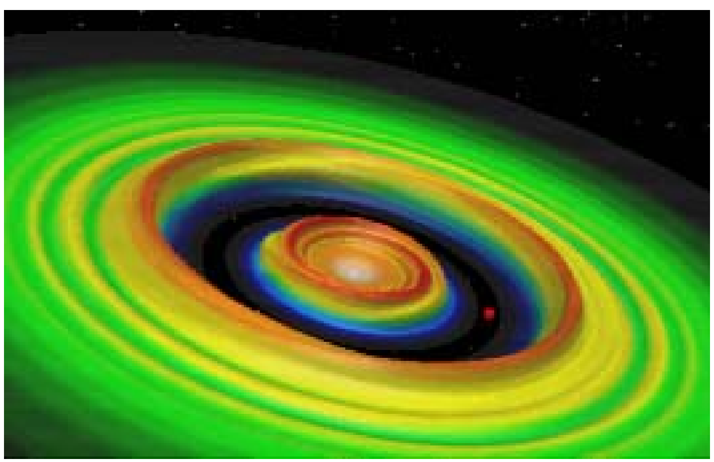


- deeply embedded multiple system
- new VLA 7mm: θ ~ 30 mas ~ 4 AU (Lim et al. 2004)
- 2 compact disks, ~ 0.05 $M_\odot$ each, 45 AU separation + other features

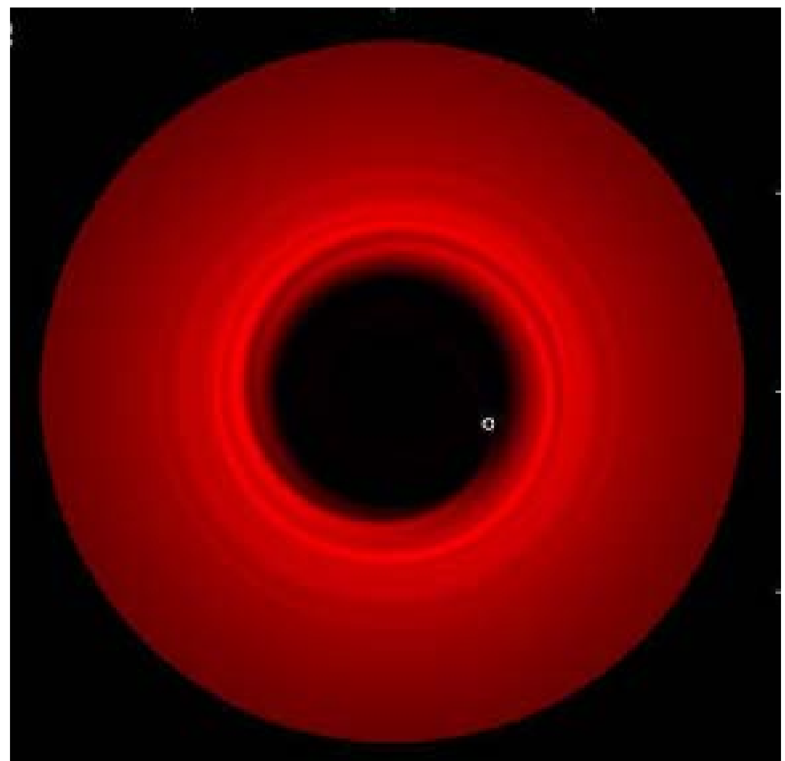
cf. Rodriguez et al. 1998

Disk Clearing: Gaps and Holes

- ir excess / accretion largely gone ~ few Myr (e.g. Haisch et al. 2002); more from Spitzer
- spectral “gaps”: TW Hya, GM Aur, CoKu Tau 4, ...
- planet formation, disk truncation?



Bryden et al. 1999

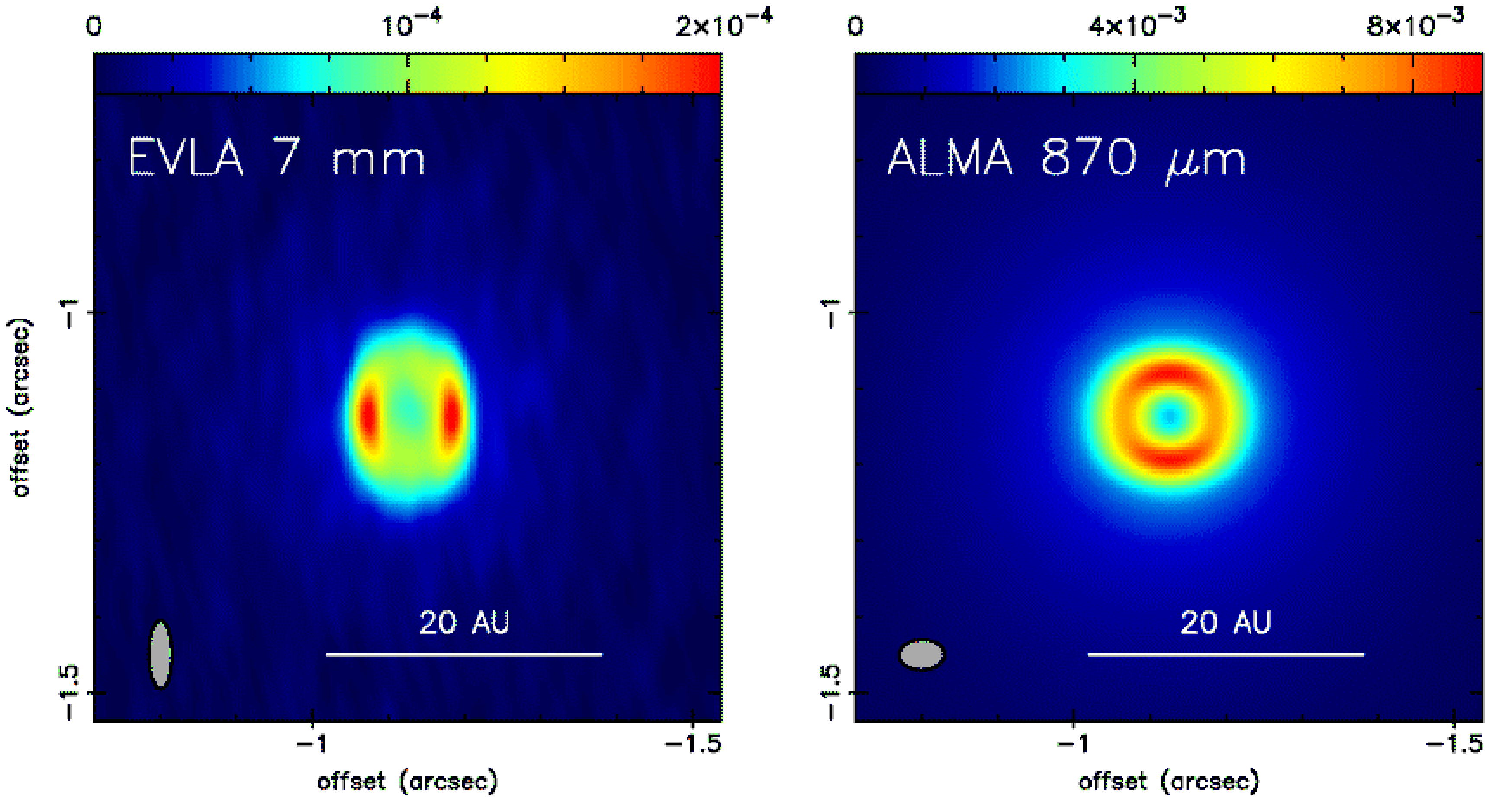


20 AU

Quillen et al. 2004 CoKu 4 Tau $0.1\ M_{Jup}$

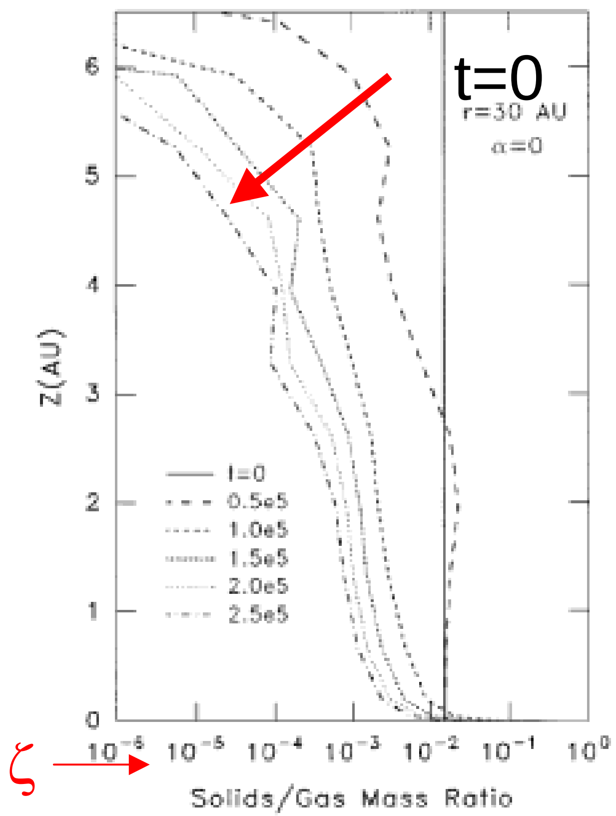
Next Generation Millimeter Imaging

- e.g. TW Hya inner hole r ~ 4 AU = 0.07 arcsec

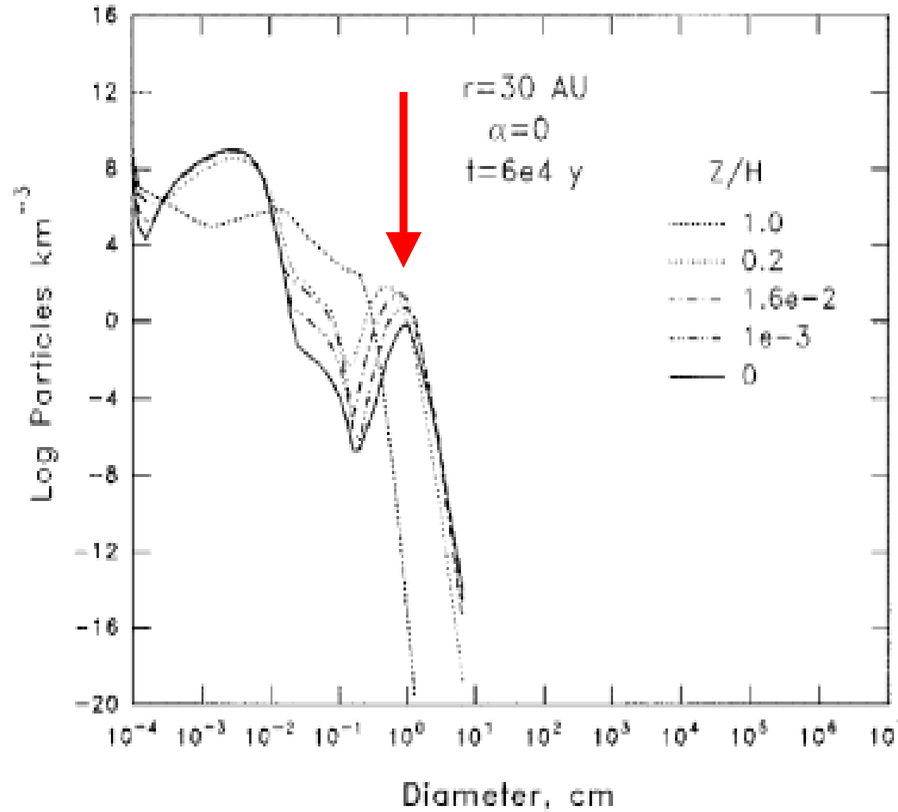


Grain Growth and Settling

decrease dust/gas in upper layers



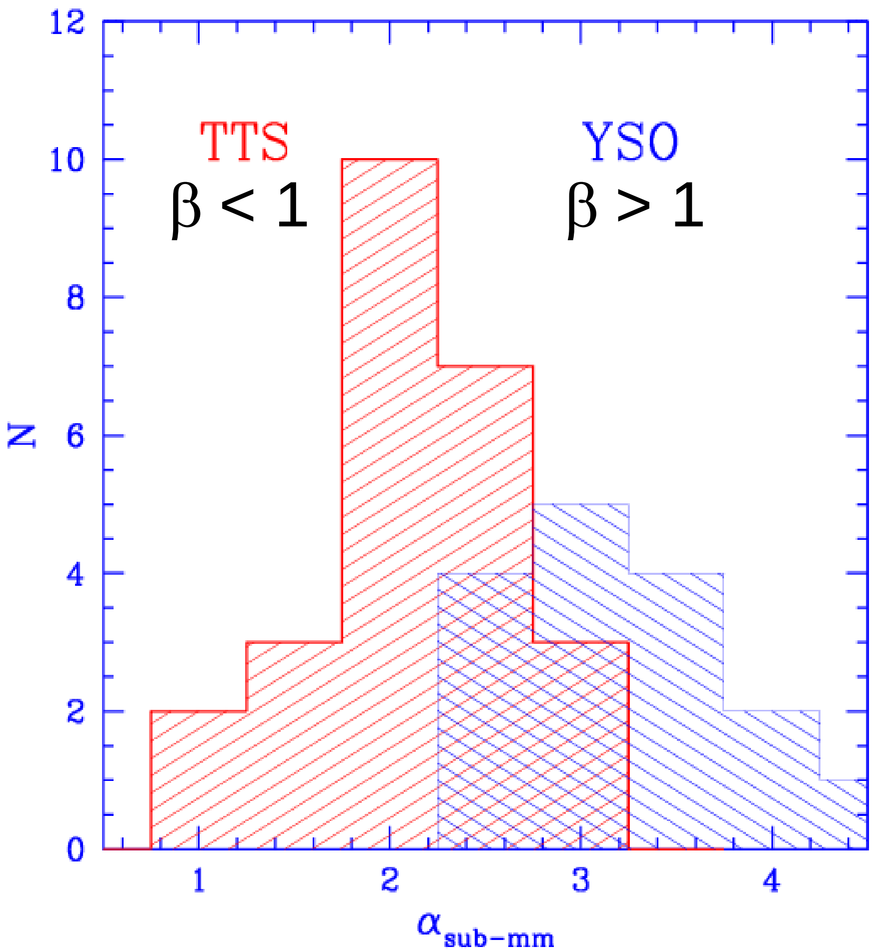
population of ~cm size grains in midplane



Weidenschilling 1997

Grain Growth and Millimeter λ's

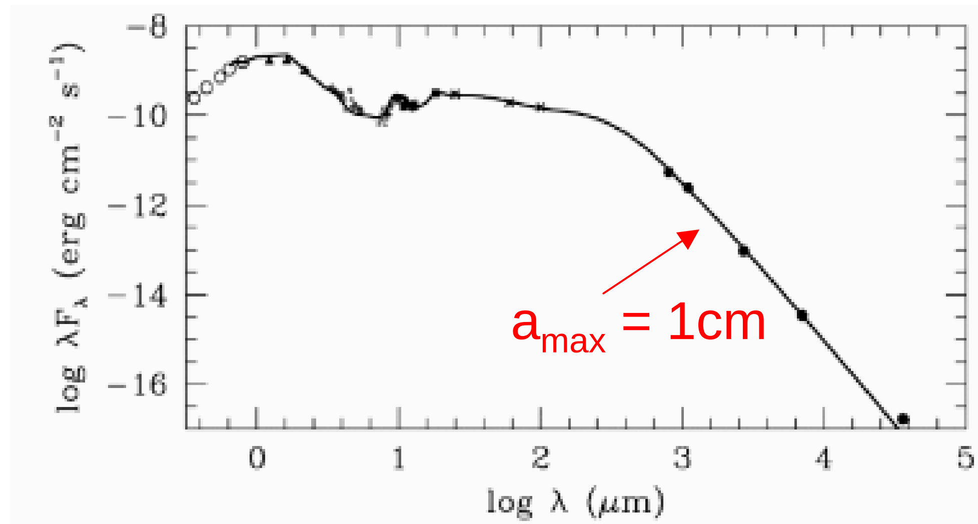
- $F_{mm} \sim \kappa_{dust}\, \lambda^{-2} \sim \lambda^{-(\beta+2)}$; if $\tau < 1$, observe β, diagnostic of dust size, shape, composition, ...
- compact spherical grains << λ, $\beta = 2$; rocks >> λ, $\beta = 0$
- if $F_{mm} \sim \lambda^2$, then large grains? or $\tau > 1$?

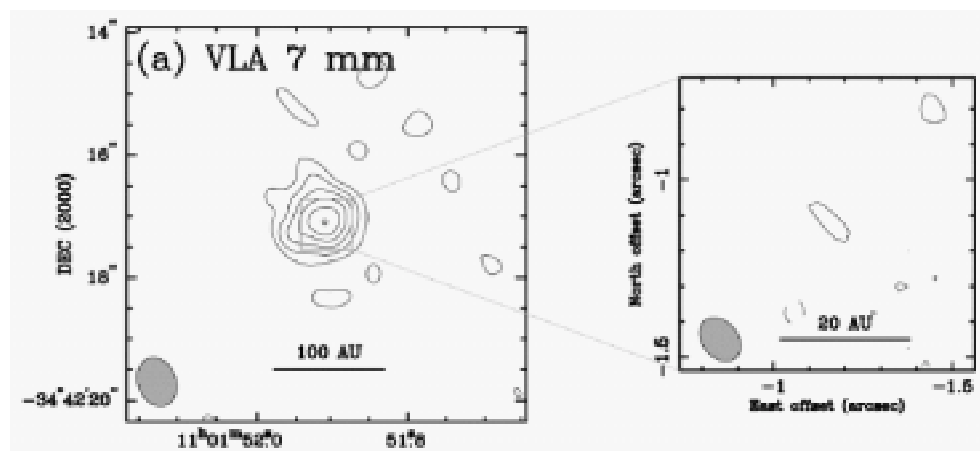


Sargent & Beckwith 1991

TW Hya Millimeter Spectrum

- spectral index from 1.3 to 7 mm ~ 2.6
- VLA resolves 7 mm emission → low T_B, models indicate $\tau < 1$, $\kappa_{dust} \sim \lambda^{-0.7}$ ∴ large grains
- more resolved disks with $\beta < 1$ Natta et al. 2004

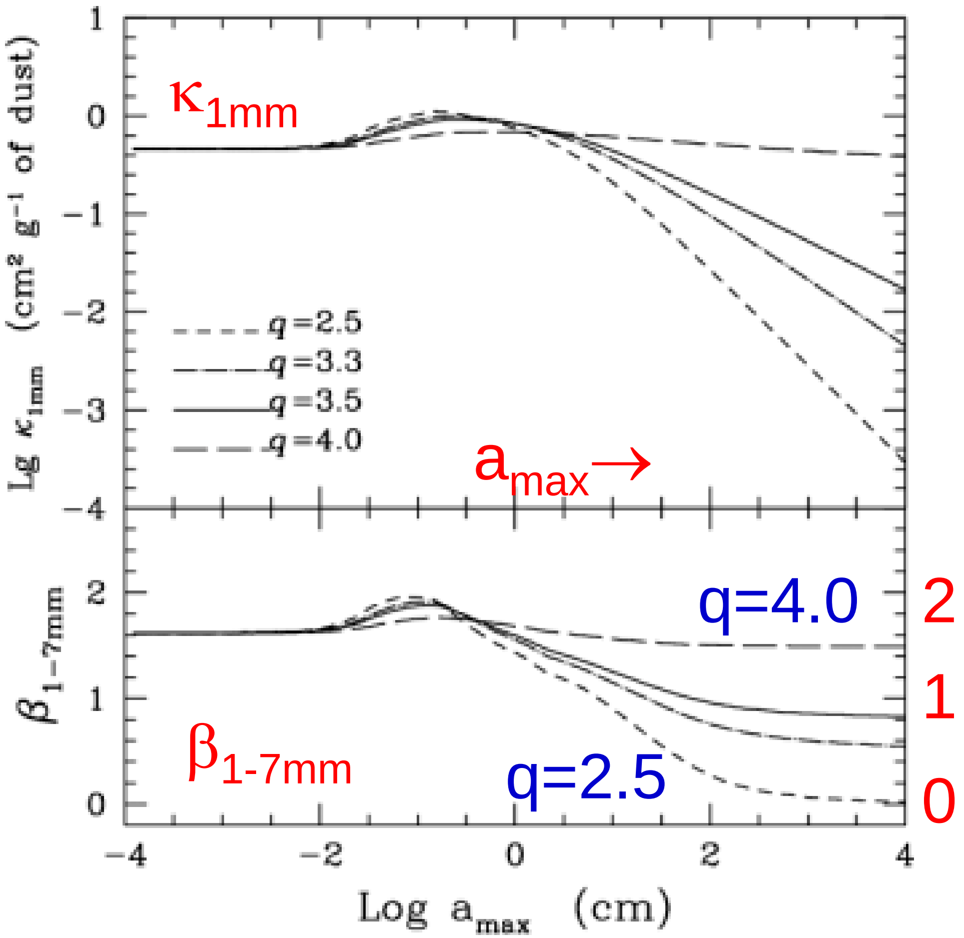




Calvet et al. 2002

Complexity in Interpretation of β

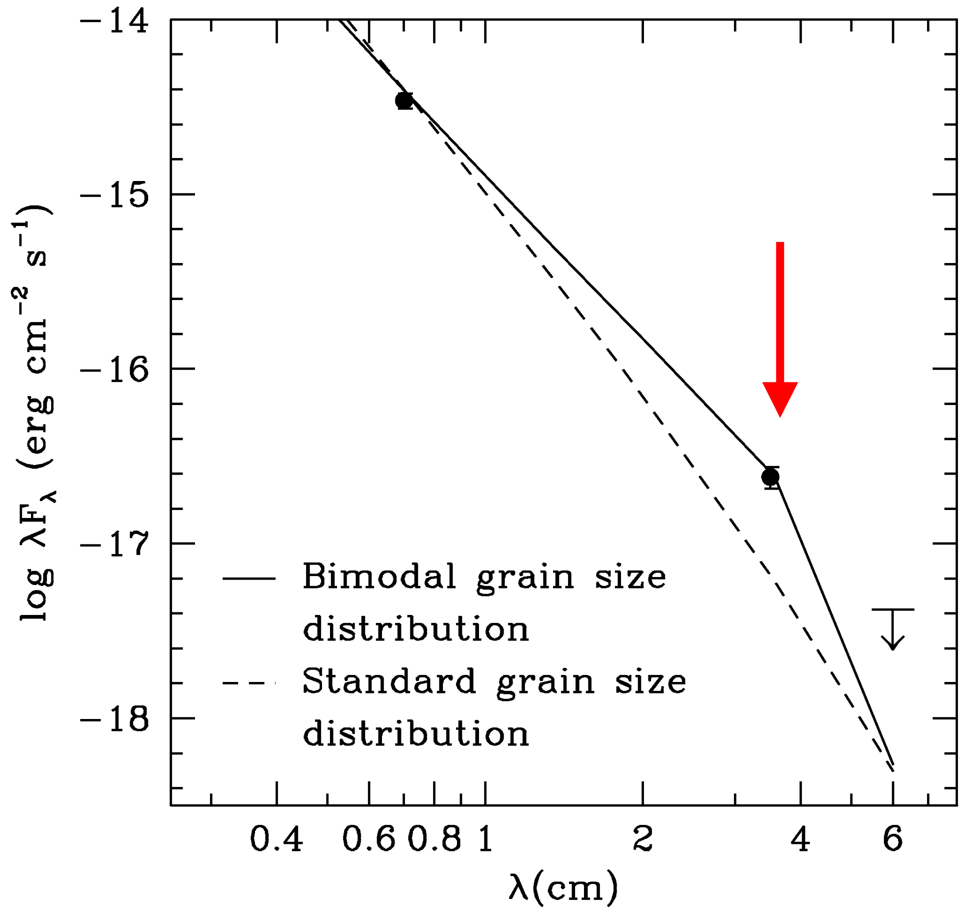
- β is an "average" for dust model
- for size power law: $n(a) \sim a^{-q}$, $a_{min} < a < a_{max}$, $\beta \to 0$ for large a_{max} only if $q < 3$
- low q: coagulation
  high q: fragmentation
- more constraints?



Natta et al. 2004

TW Hya at 3.5 cm: Dust Emission

- 3.5 cm ~ 260 μJy
- resolved by VLA, T_B ~10 K, not variable, ↓6 cm
- not stellar activity, not T Tauri wind
- (very) large grains, 99.9% mass frac.?



Wilner et al. 2004

Summary

- millimeter = few 0.1's mm to few 10's mm
- tracers of "cold" H_2 : dust and molecules
- interferometry: typically ~ arcsec
  - dust (low τ) $\rightarrow$ $\Sigma(r)$; mass and mass distribution
  - ^{12}CO (high τ) $\rightarrow$ $T(r)$; other lines (low τ) $\rightarrow$ $f(r,\theta,z)$
- resolved kinematics: Keplerian rotation (and M_*)
- physical models: irradiated, flared, accretion disks (e.g. TW Hya, DM Tau); tidal truncation
- dust spectra: grain growth evidence
- amazing future prospects: ALMA, EVLA